Combined Space and Ground Based Tomography

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LONG-TERM GOAL

The long term goal of this research is to accurately specify the ionospheric electron number density throughout a large spatial region, continuously in time. In addition, a second long term goal is to combine this high resolution regional specification with a lower resolution global specification to provide to the application and scientific community a continually updated global ionospheric specification with (several) high resolution regional specifications.

OBJECTIVES

The primary scientific objective of this research is to develop a prototype algorithm for combining several types of ionospheric remote sensing data sources. These data sources will be made up of both ground and spaced-based sensing methods. The algorithm will take the multiple data sources as input, and will output three dimensional (3D) specifications of the ionosphere at regular time intervals (default = 30 min.). The secondary objective of this research is to investigate and characterize the accuracy of the specified ionosphere by comparing it with independent measures of the ionosphere.

APPROACH

The previous year research resulted in an initial implementation of a 4D CIT algorithm. This algorithm was based on combining 2D GPS TEC maps with 2D CIT reconstructions with a sophisticated interpolative method. The method is described in the previous year's report.

This year an entirely new algorithm was developed that was truly 3D in nature. The approach adopted was to create an algorithm that could accept any kind of 3D linear integral over the electron density. This would include line-of-sight GPS TEC, CIT beacon TEC, low earth orbiting (LEO) GPS TEC, and satellite EUV measurements. Like the previous algorithm, the new algorithm updates its specification of the regional electron density at regular time intervals (default = 30 minutes). However, from analysis of the results and performance of the previous algorithm, it was determined that several significant outstanding issues still needed to be resolved. The issues addressed are:

1. The requirement for an initial background ionosphere for the CIT processing, that is not limited by empirical climatalogical models.

2. The requirement for a sophisticated method of estimating the CIT receiver biases.

3. The requirement for estimating the plasmasphere contribution to the GPS TEC measurements.

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4. The requirement for an improved method of estimating the GPS slant TEC biases

5. The requirement for a realistic estimate of the error on the CIT specified electron density, and a subsequent "objective analysis" on the electron density field.

The approach adopted in the new algorithm to address these issues is as follows:

1. The CIT specified ionosphere at time t1, is used as the initial background ionosphere at time t1+ delta_t. This removes dependence on a climatalogical model, and assumes that over time, the new algorithm converges to a specification of the ionosphere that is more accurate than an empirical model gives. In addition, the assumption is for a delta_t of 0.5 - 1 hour, the changes in the ionosphere slow enough that using a specification from 0.5 -1 hour old is a good initial guess.

2. The new algorithm iteratively solves for the receiver biases, along with the electron density. The SIRT algorithm, takes all the data, computes a single correction for each electron density point, and then updates the density. Following that, the predicted TEC for each receiver is compared with the data TEC + the current bias estimate. An average difference is computed, which represents the change in bias required to achieve the best agreement. During the development phase, it was found that after 5 iterations, the residual bias change was < ~ 0.05 TECU, which is on the order of the expected noise on the data. Thus, the completed algorithm iterates on the biases for 5 iterations, then freezes them for the rest of the SIRT reconstruction process.

3. The new algorithm includes a very low resolution grid in the plasmasphere, and solves for the plasmasphere in a method that is identical to the method used on the ionosphere.

4. We have a method developed by Dr. Coco for estimating GPS TEC biases that we have used for several years. It is a good method, but still leaves errors on the slant TEC of greater than 1-3 TECU. For tomographic reconstructions, those errors are too large. So the approach adopted in the new algorithm is to compute residual bias corrections for GPS *at times when there is CIT data.* The reasoning being that after the algorithm has specified the electron density during a CIT data time, the electron density specification will be its most accurate, and more accurate than any empirical model. Thus, it can be used to compare predicted TEC with the GPS data and compute a bias correction. A running average of corrections is kept, and after several days of running the algorithm, the GPS biases settle down to residuals < ~ .5 TECU.

5. The approach adopted to estimate the CIT reconstruction accuracy uses a combined measure of how strong the data effects a given voxel, and how time late the data has effected a given voxel. The algorithm is designed such that if 4 or more data "rays" from independent receivers cross through a voxel at the reconstruction time, then the error on that voxel is as small as we ever expect tomography to provide (currently set at 10%). Then the error increase as less rays intersect the voxel, limited by the fact if no rays intersect the voxel, then in a weighted "objective analysis" we would want the analysis to use climatology at that voxel. In addition to weighting by the number of data rays, we also consider the time history of data rays intersecting a voxel. For example, if a data-rich CIT pass occured 1 hour ago, and many voxels had 4 or more rays passing through them, it is expected that those results still have validity. The approach we have adopted is to allow an exponential decay in the accuracy. We choose a decay time of 3 hours, when we are not near the terminators, and we choose 0.5 hours during the terminator. The weight matrix is saved for each reconstruction epoch. Upon initialization of the next reconstruction process (30 minutes later for

example), the weight matrix is read in, and a weighted estimate of electron density is made using the previous CIT specification, and a climatological model (currently IRI90). Where there has been recent good data the objective analysis weights heavily towards the CIT specification. In regions where either there has been no data, or the data is old, the analysis weights toward climatology.

WORK COMPLETED

For the original interpolative algorihm, ionosonde data has been added to GPS TEC and CIT reconstructions and the algorithm has been refined and made more robust. To reflect the interpolative nature of the algorithm, it has been renamed the Tomographic Reconstruction by Interpolation and Mapping (TRIM4D) method. In addition, this algorithm has been transitioned to DoD systems work being performed by another division within our group.

The new algorithm has been implemented tested, and applied to several data sources. All the components described in the approach section have been implemented. In addition, if ionosonde data is available, it is also used as part of the objective analysis module. Finally, several user options have been implemented that allow control over whether SIRT, ART or MART is used as the reconstruction engine, whether to iteratively improve the biases, and whether to weight the reconstruction corrections by the electron density (the default is to weight by the length of the ray through the voxel).

The algorithm has been tested on several days of data from August 1997, and has performed well.

RESULTS

The TRIM4D algorithm has been transitioned to a DoD Navy application research area here at ARL:UT. The systems people have rewritten it in C++ and made it more robust. The application area of interest requires transionospheric time delay corrections. Figure 1 shows an example of the corrections that TRIM4D when combined with a 3D raytrace program is making.

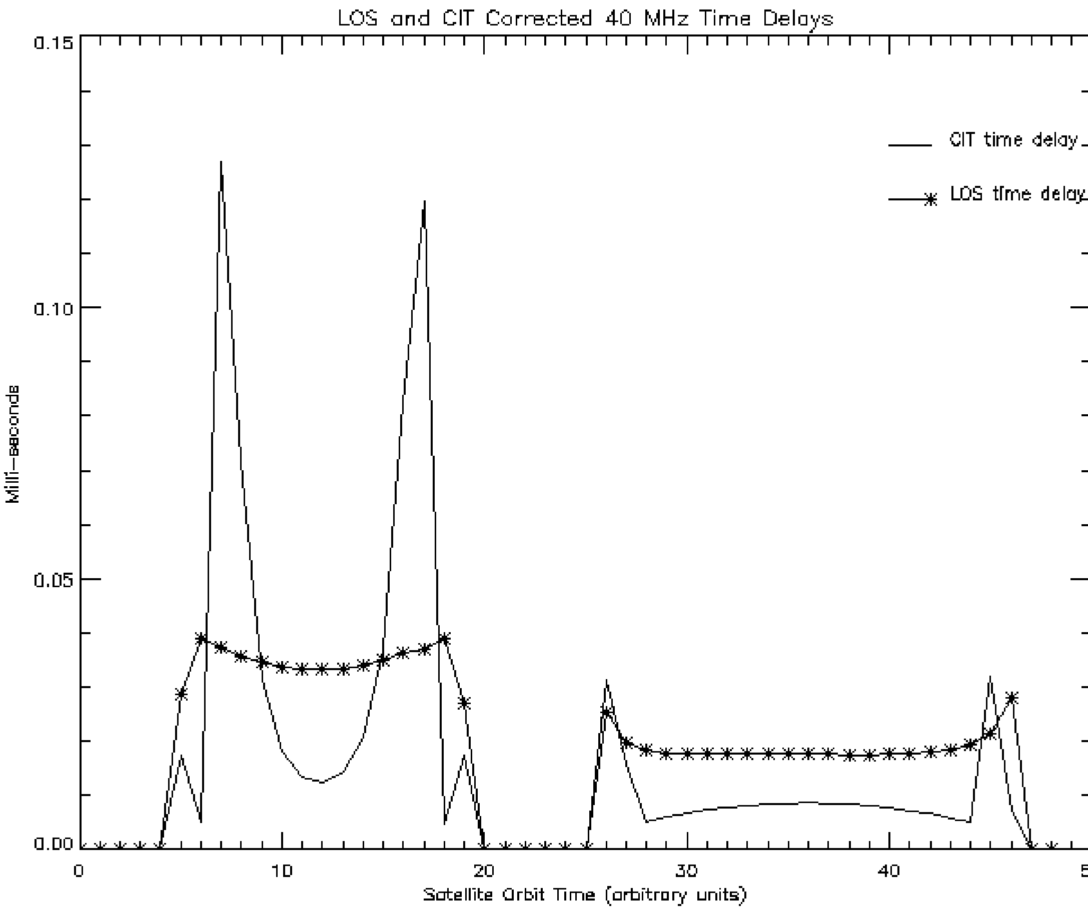

Figure 1: Transionospheric VHF time delay corrections

The new algorithm has been applied to some of the Caribbean data and works well. The results are consistent from 30 minute update to 30 minute update. Figures 2-4 show the specified electron density at three different times on 8/14/1997.

Currently, the new algorithm is being applied to a 1 month data set collected by ARL:UT in 1996. The data set consisted of thee six receiver arrays located on the Eastern USA. The results will be compared against ionosondes, and an average deviation error in the fof2 will be computed. In addition, the results will be compared against the ISR at Millstone Hill, which was on for 5 days during the collection period.

The new algorithm is also being applied to the over-the-horizon (OTH) targeting and tracking problem in collaboration with researchers at Mission Research Corporation (MRC) and UCLA.

Finally the new algorithm is being applied to the CIC data campaign and the Puerto Rico HF heater campaign data set from January 1998.

IMPACT/APPLICATION

The two algorithms have demonstrated the capability to provide high resolution, accuracy specification of regional electron density during both quiet and disturbed times. The algorithms are being used to

investigate the mid-latitude and low-latitude response of the ionosphere to geomagnetic storms. The 3D ionospheric specification will also be an important data source for the new data assimilative ionospheric models now being developed. Part of the research undertaken during this project, is to accurately characterize the error on the tomography specification by comparing results to ionosondes and ISR's.

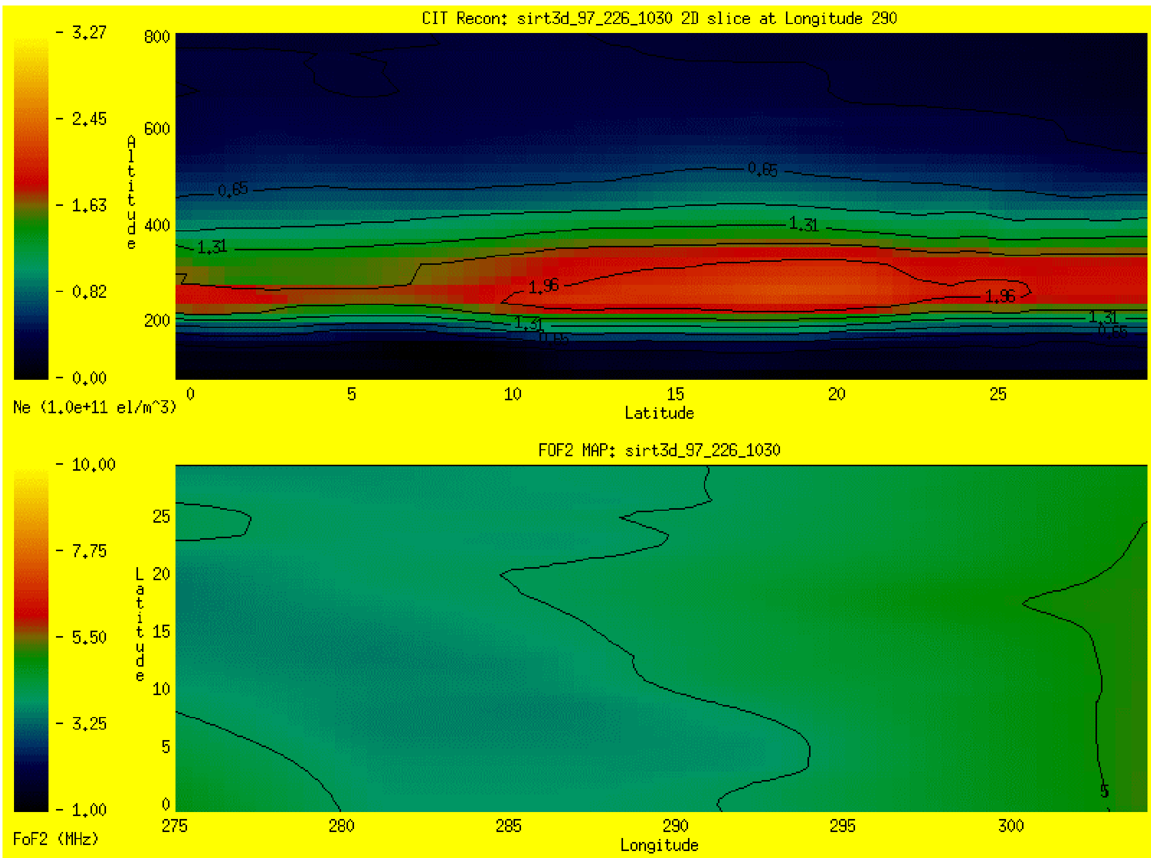

Figure 2: Caribbean CIT Reconstruction 10:30 UT Aug. 14, 1997

TRANSITIONS

The initial algorithm developed under this research program, TRIM4D has been transitioned to the Satellite Geophysics Division (SGD) here at ARL:UT and is being used as part of their ionospheric data correction program with NRO.

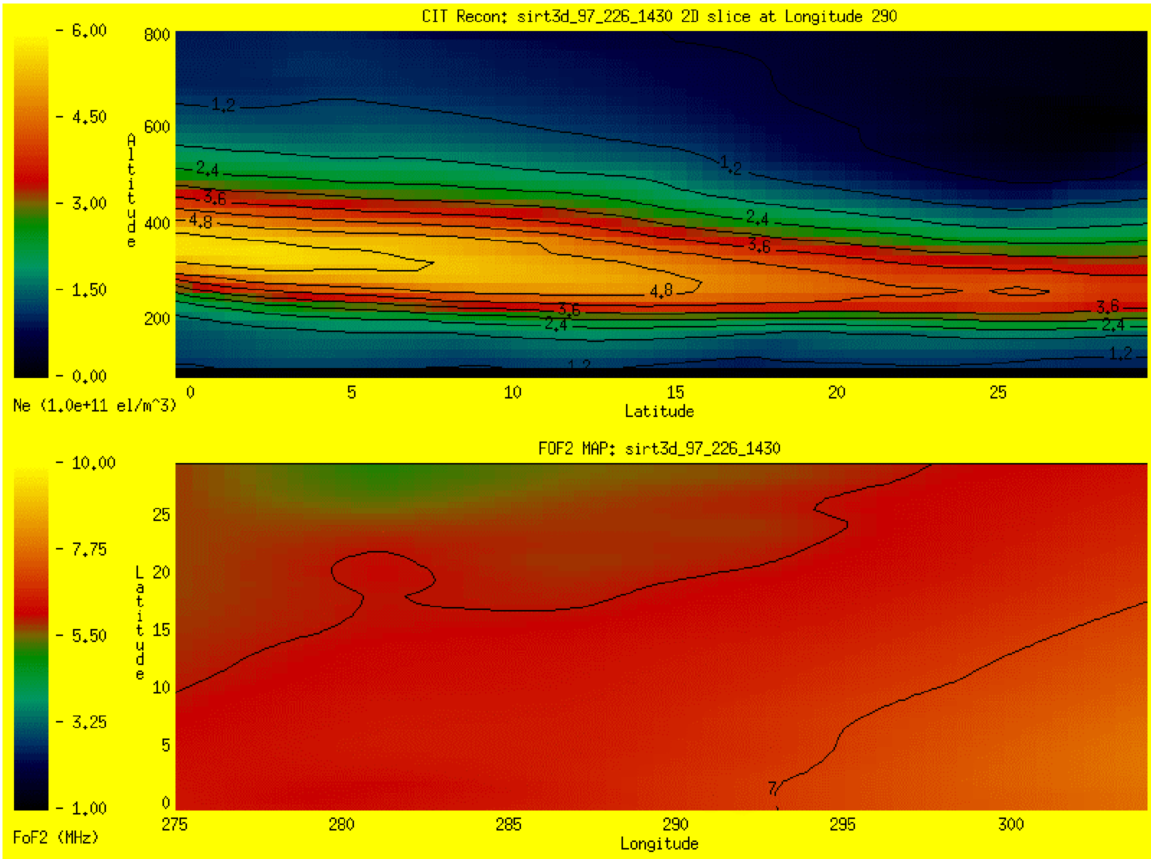

Figure 3: Caribbean CIT Reconstruction 14:30 UT Aug. 14, 1997

RELATED PROJECTS

- The transionospheric data correction project described above makes use of this project results.
- The OTH program at ONR under Dr. Bill Stachnik makes use of the algorithms developed under this research.
- A new NSF project, to estimate the E-region electron density at high latitudes will make use of the results obtained from this project.

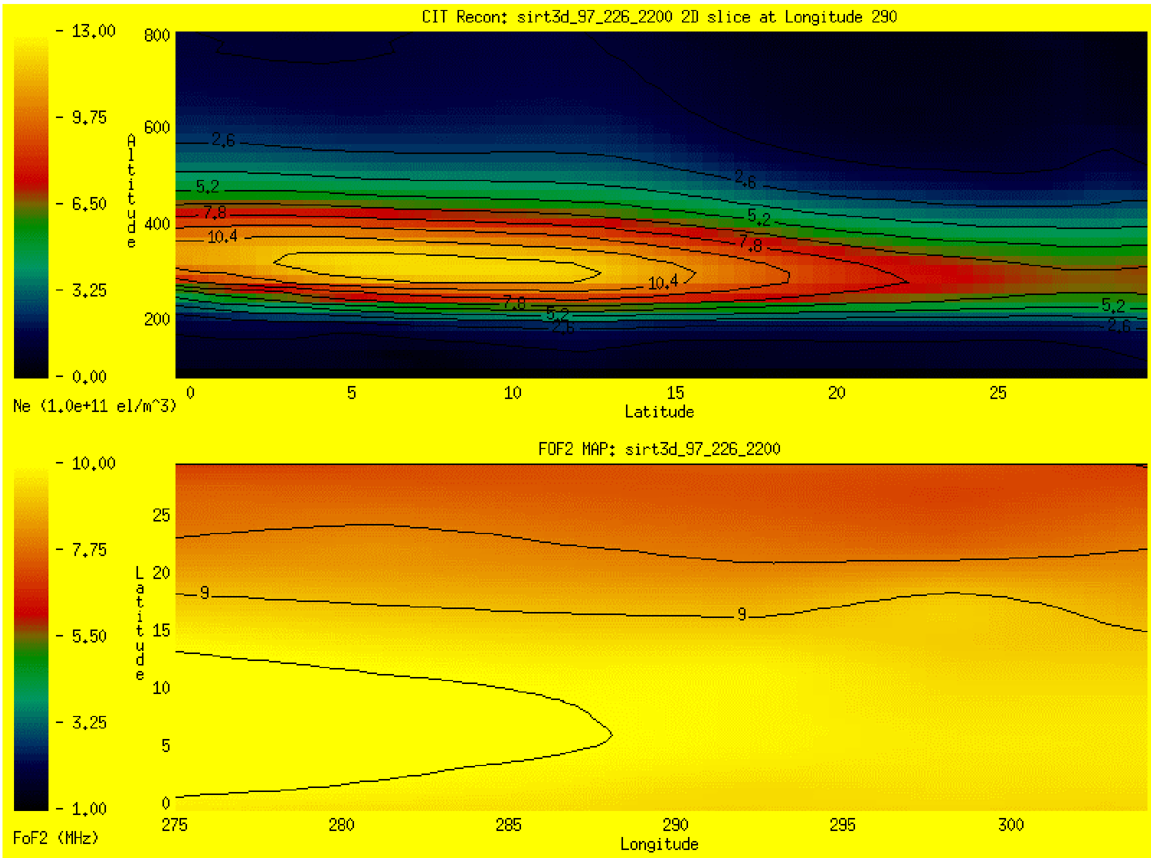

Figure 4: Caribbean CIT Reconstruction 22:00 UT Aug. 14, 1997